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Modelling Population Exposure to Traffic Air Pollution Using GIS

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Abstract

The paper outlines the background, methodology and perspectives for an ongoing PhD project with the objective to develop a model for population exposure to traffic induced air pollution in order to improve assessment of health impacts and impacts of various traffic control strategies. A selected urban area will be used as a case study. The model will combine modelled air pollution data using the Danish Operational Street Pollution Model (OSPM) and population data using a Geographic Information System (ArcView). A simple population dynamics model will be established to model the number of people which simultaneously are present in a given area during a given time.

1. Key Components and Factor of Health Assessment

Conceptual Health Risk Assessment Model

A comprehensive health risk assessment may be considered as a chain of components including emissions, ambient air pollution levels, exposure, dose and effect as illustrated in figure 1. The main factors that influence the five components are also illustrated. (Elaboration on risk model based on Ott (1985) and Hall (1996)).

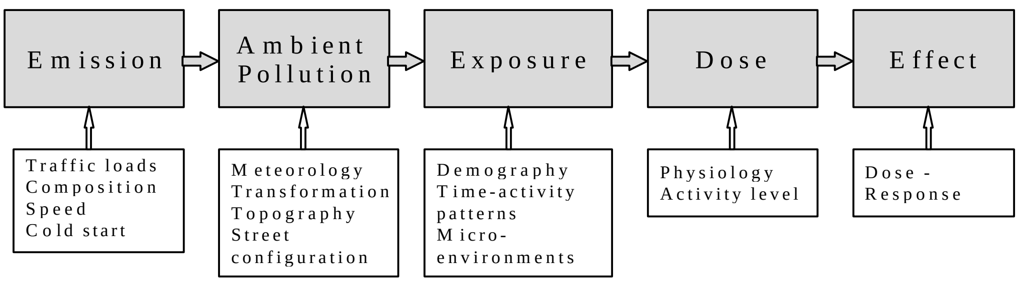

Figure 1 Key Components and Factors of Health Assessment of traffic Air Pollution

Exposure Assessment in Health Risk Assessment
Health risk assessment of air pollution combines exposure and health effect assessment. Health effects assessment is based on identification of the toxicity of a pollutant and its effects through epidemiological studies, and human and animal experimental studies. Based on these studies dose-effect relations are established, and dose-response describing the frequency of a health effect in a population. The next step is to determine the number of people exposed to various pollutants and levels. Based on the established dose-response relations and the exposure assessment a health impact assessment can be carried out to quantify the health effects among a population at present air quality levels.

Exposure Assessment - the Missing Link
Knowledge about all components from emissions to effects is crusial in health assessment. Air pollution studies including compiling emission inventories and monitoring as well as modelling of ambient air pollution have been carried out without much link to health effect studies. Further, until now only few studies have been performed to determine the exposure and dose of different population groups. These "missing links" are a problem in health risk assessment when information on ambient air pollution and health effect studies are going to be combined, and information is lacking on who, where, how many and for how long time people are exposed and at what dose.

Exposure Factors
Exposure is defined as a person's contact with a pollutant of a certain concentration during a certain period of time. For example, a person who stays one hour in an urban street may be exposed to a mean NO_2 concentration of 200 µg/m^3. The dose (µg) is the amount of inhaled air (m^3) times the concentration of the pollutant (µg/m^3). The dose will be depending on the person's physiology (age) and activity level. The absorbed dose is the fraction of the dose that is absorbed by the organism.

The exposure of a person will be depending on the person's time-activity pattern and the concentration levels in the visited microenvironments.

A microenvironment is a location that is assumed to have homogeneous pollution concentrations patterns in time and space e.g. at home, at work, in a street etc. (Williams, 1991), (Sexton and Ryan, 1988).

A person's time-activity pattern describes how long time a person stays in different microenvironments and the person's activity level in these microenvironments. Time spent is related to exposure and activity level is related to dose (Ackermann-Liebrich et al.,1995).

As people spend most of their time indoors, the indoor - outdoor ratio of pollutants (I/U ratio) which can refer to both buildings and e.g. vehicles becomes important. Indoor sources to air pollution e.g. gas stoves are therefore important (Yocom, 1982).

2. Introduction

2.1 Background

Road Transport Dominant Source
Road transport has become the dominant source to air pollution especially in larger urban areas due to increase in passenger and goods transport and due to tighten emission standards for other

sources like power plants and industries. In trafficked urban streets the contribution from traffic may constitute 80 to 90 per cent. Despite stringent emission standards for cars, air pollution from traffic is expected to dominate air pollution in cities in the years to come.

Guidelines and Levels

Present Danish air quality standards are not exceeded. However, less stringent air quality guidelines for the irritant NO_2 is tangented or exceeded at several fixed monitor stations in Copenhagen, and recent measurements of the carcinogenic substance benzene far exceed the guidelines of the World Heath Organisation (WHO). Present air quality guidelines are under revision and are expected to be stringent.

Fixed Monitor Stations Are Poor Exposure Indicators

Population exposure assessments are usually carried out based on fixed stations in air quality monitoring programmes assuming that these stations are good indicators for population exposure. However, this is a very rough assumption as argued below.

In Denmark, there are three types of stations in the Danish Air Quality Monitoring Programmes: street, urban background and rural background stations. Stations in heavy trafficked street canyons are established to measure worst case conditions for comparison with air quality guidelines. However, from an exposure point of view people spend little time in these microenvironments. Urban background stations are located in the centres of large cities at roof top level (height approx. 20 m) to determine urban background levels which primary serves research requirements. The difference between concentrations in streets and in the urban background may be a factor of 2 for NO_2 and a factor of 10 for CO. Rural background stations are located in remote areas primary to determine long-range transport of air pollutants to Denmark and deposition to forest, agricultural land, in-land waters and inner seas. Few people live in these areas.

Fixed stations represent outdoor levels and most people spend more than 90 per cent indoor. Furthermore, individuals may have very different time-activity patterns e.g. differences in time spent indoor and outdoor, and differences in time spent in different microenvironments e.g. streets, urban centres, suburb, work environment etc.

All in all, the coverage and the representativity of the stations in the monitoring programmes are too limited for more detailed exposure assessment. Therefore, fixed monitor stations are poor exposure indicators.

Health effects of Air Pollution

Health effects of air pollution can be difficult to assess since many compounds are present at the same time and it is difficult to isolate factors related to air pollution from other factors.

A threshold value exists for some pollutants which has to be exceeded to cause a health effect e.g. irritants like NO_2 and O_3. For other pollutants no threshold value is expected to exist, e.g. carcinogenic pollutants like benzene. Numerous studies indicate that air pollution increase the risk for development of cancer, allergy and air ways diseases or aggravate the condition of people suffering from air ways or heart diseases. Especially sensitive groups are at risk for increased morbidity or premature death e.g. weakened or sick people, people with air ways and heart diseases, and children and elderly people. Short-term exposure with high concentrations of NO_2 or O_3 may cause inconvenience or nuisance to people suffering from air ways diseases and long-term exposure with hydrocarbons like benzene may cause cancer. Particles as carriers of carcinogenic pollutants can contribute to development of cancer. Further, fine particles ($PM_{2.5}$ or PM_{10}) are claimed to cause increased morbidity and premature mortality (Larsen et al., 1996).

Rough Exposure Assessment
All other things equal, the ambient air pollution concentrations will increase with increasing city size, with traffic intensity in street environments, and decrease from the city centre to the outskirts and further to the rural areas. In Denmark, about 1.8 million people live in the Greater Copenhagen Area and other cities with more than 100.000 inhabitants where relatively high air pollution levels can be expected. About 1.1 million people live in medium sized cities with moderate air pollution levels and 2.3 million in small towns, villages and rural areas with low air pollution levels. People living along busy streets will experience high exposure to air pollutants from traffic. About 0.3 million people live along streets with high traffic levels based on residences exposed to high levels of traffic noise (above 65 dB(A)). About 24.000 people in Copenhagen live along streets where the recommended guideline for NO_2 is violated based on modelled concentrations by the Nordic Street Pollution Model (BLB) (Jensen, 1996).

Rough Health Impact Assessment
A health impact assessment covering a quantification of the health effects of traffic air pollution has not been carried out in Denmark. The traffic induced air pollutants that raise most concern are: particles, NO_2, O_3, PAH, benzene, 1,3-butadiene, ethene and propene, and aldehydes (formaldehyde, acrolein, acetaldehyde) (Larsen et al., 1996). Several Danish reports claim that air pollution levels in Denmark cause health effects although present Danish air quality guidelines are not violated. If the results of comprehensive epidemiological studies carried out in USA are transferred to Danish conditions a premature mortality of about 400 occurs annually in the Greater Copenhagen Area due to present concentrations of fine particles (Moseholm, 1994). Rough assessments of the impacts of PAH, benzene and 1,3-butadiene suggest that these pollutants may cause in the order of 75 - 150 excess cancer incidents in Denmark (Larsen et al., 1996). Furthermore, the prevalence of asthma and bronchitis is high causing irritation to many people when exposed to NO_2 and O_3. About 0.5-1 per cent excess days lost trough sickness in Copenhagen have been suggested (Moseholm, 1994). Although the uncertainty is large on the above rough quantification of the health impact the figures suggest that the health impact of air pollution may be at the magnitude of traffic accidents (about 650 annual deaths).

Exposure Modelling in other Countries
At present, there are no Danish models available for population exposure assessment. Various exposure models have been developed like the American models: National Air Quality Standards Exposure Model (NEM), Simulation of Human Air Pollution Exposures (SHAPE) and Human Exposure Model (HEM II) (Ott, 1985) (Sexton, Ryan, 1988) and the Dutch Air Pollution Exposure Model (AirPex) from the National Institute of Public Health and the Environment (RIVM). These models have been developed for specific purposes and are not directly transferable to a Danish context.

2.2 Aims and Objectives

The research project includes:

(a) Identification of pollutants relevant for human exposure modelling
(b) Assessment of important exposure factors like time-activity patterns
(c) Assessment of various methods to develop exposure models using Geographic Information Systems (GIS)

(d) A case study for a selected urban area. The model will combine modelled air pollution data using the Danish Operational Street Pollution Model (OSPM) and population data using a Geographic Information System (ArcView). A simple population dynamics model will be established to model the number of people present at a given area during a given time. The population dynamics model will be based on data for residential population density and density of employees in business and industrial areas using existing registers established by the authorities. Furthermore, statistics concerning time-activity pat terns will be used to establish simple profiles for time spent in the various areas. Time spent in streets will also be assessed. Additionally, ratios between indoor and out door concentrations will be taken into account

(e) Apart from population exposure assessment using the above method personal exposure assessment of hypothetical representative individuals will be modelled as case examples

(f) Examples of health risk assessment

(g) Examples of impact assessment of selected traffic control strategies applying the developed exposure model.

2.3 Context

The PhD project is related to two ongoing research projects under the Danish Strategic Environmental Research Programme (Strategiske Miljøforskningsprogram): the “Childhood Cancer Project”, and the project about “Exposure of Bus drivers and Postmen”. Furthermore, it is related to two other projects: “Health Risk Assessment” and “GIS-T”.

Childhood Cancer Project

The Childhood Cancer Project is a population-based case-control study of about 7,500 children born after 1960. It is the aim of the pro ject to evaluate the importance of the air pollution by car exhaust on the risk for development of childhood cancer (Raaschou-Nielsen et al. 1994). The study is conducted by the Danish Cancer Society and carried out dur ing 1994-1997.

Part of the project is to model the air pollution levels at the address(es) of the children during their childhood using a tool based on the Danish Ope rational Street Pollution Model (OSPM) developed by the National Environmental Research Institute (Berkowicz et al. 1994). A sub-study entitled "Exposure of Danish children to traffic exhaust fumes" evaluates the measured per sonal exposure of 200 children to NO_2 and BTX (benzene, toluene, xylene). The objective of the project is to validate a tool for childre n's exposure to traffic air pollution for applica tion in the case-control study (Raaschou-Nielsen et al. 1995).

Part of the PhD study is to provide standardised temporal variations of rural and urban background concentrations (trends, seasonal and monthly diurnal variation) together with standardised temporal variations of traffic (trends, seasonal, weekly and diurnal variation) as necessary inputs for the above air quality calculations. These results will also be applicable to the PhD project.

Exposure of Bus drivers and Postmen

The second project is an exposure study aiming at development of an exposure model for bus drivers and postmen under normal working conditions. The exposure model will be developed by the National Environmental Research Institute and be based on OSPM. The study also includes personal monitoring of NO_2, PAH, particles and elements, and biological monitoring of PAH for comparison with personal monitoring. Especially the indoor - outdoor ratio of air pollution for buses will be of interest to the PhD project (Breum et al., 1995).

Health Risk Assessment
The Danish EPA is heading a study on health risk assessment of traffic air pollution in co-operation with the Institute of Toxicology at the National Food Agency of Denmark and the National Environmental Research Institute. Part of the PhD study is to prepare a chapter of the report on “Population Exposure” which is to be published in 1996 (Larsen et al. 1996).

GIS-T
The Institute of Roads, Traffic and Urban Planning (IVTB), Technical University of Denmark (DTU) has initiated a research project on the application of Geographic Informations Systems (GIS) in traffic planning (Nielsen & Jacobsen, 1995). The PhD project will make use of data generated in this project for an urban case study. In co-operation with IVTB the National Environmental Research Institute has started a project to adjust OSPM to the GIS environment to facilitate air quality mapping. This work is carried out by colleagues at NERI and will be very useful for the PhD project when ready.

3. Methodology of Exposure Modelling

Outline
The approach for modelling population exposure is to combine modelled air quality concentrations in different microenvironments of an urban area with a simple modelling of the number of people present in the same environments. Geographical Informations Systems (GIS) will be used for the analysis. The method is an indirect exposure determination based on a microenvironment approach and the approach will rely on presently available data and statistics. The methodology is illustrated in figure 2.

Air Quality Modelling
Air quality concentration levels will be determined using the Operational Street Pollution Model (OSPM) that calculates ambient hourly concentration levels based on inputs of the street configuration and hourly inputs of traffic emissions, meteorological parameters and urban background concentrations. Traffic emissions will be estimated based on Average Daily Traffic, the percentage of heavy vehicles and the travel speed for each street assuming a default seasonal, weekly and diurnal variation in traffic loads. M eteorological parameters and urban background concentrations will be extrapolated from fixed monitor stations or possibly be modelled. Pollutants will include: NO_2, CO, O_3 and possible benzene.

To determine concentration levels indoor empirical I/U ratios for the various pollutants will be applied for buildings and means of transport (cars and buses).

The urban area will be divided into microenvironments e.g. street, residential, business and industrial
environments. One of the objectives of the project is to determine the details of this division.

Modelling Population Dynamics
Economically, it is impossible to assess exposure of a large population using personal monitoring, and it is also impossible to model the exposure of each individual in a city due to the data requirements. Therefore, modelling the activities of people in a city has to rely on statistical data. Time-activity patterns have not been carried out in Denmark from an exposure point of view. However, some statistical population data is available on how time is spent in daily life and on transport (Andersen (1988), Trafikministeriet (1994)). Based on available statistical data default diurnal variation of time spent in various microenvironments for different population groups will be established.

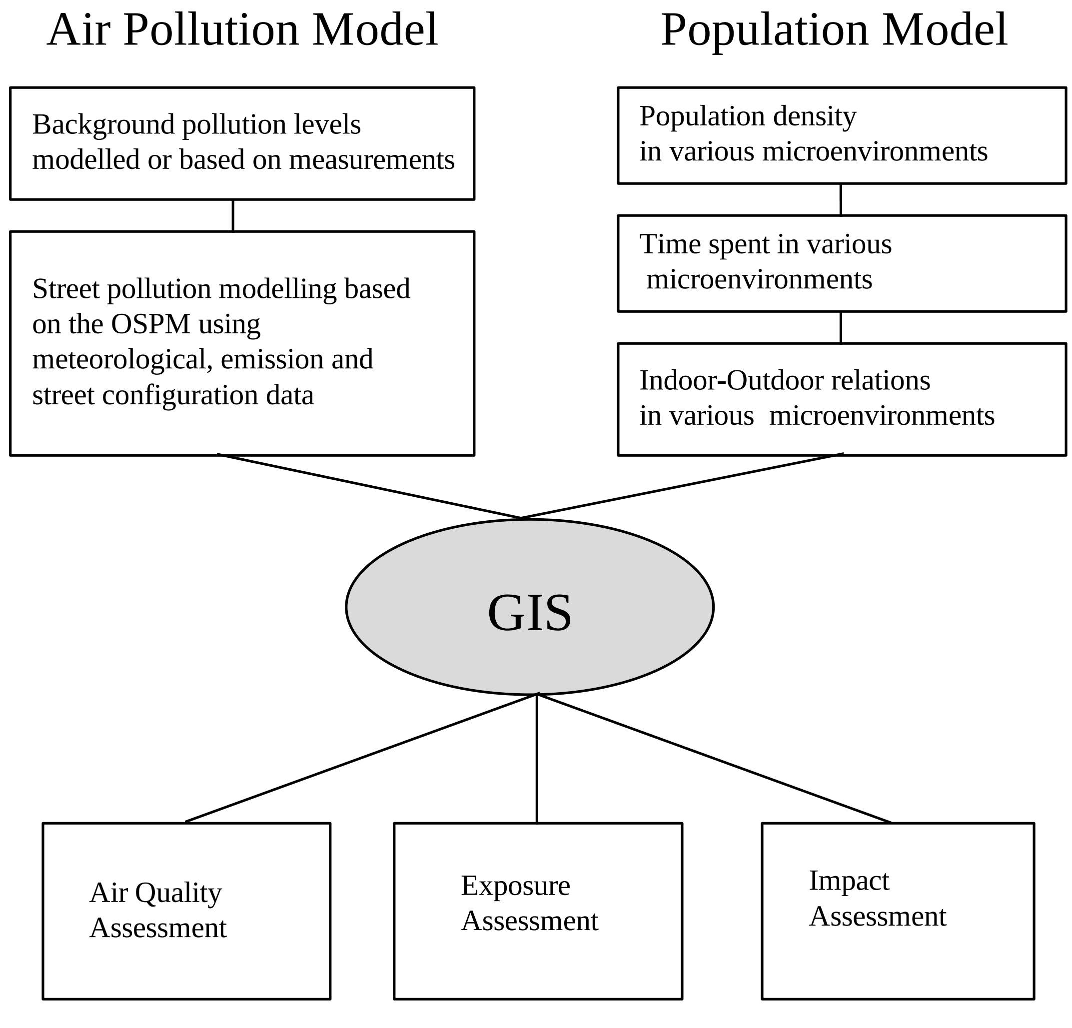

Figure 2 Diagram of the project's methodology of population exposure modellering

The authorities manage a number of comprehensive and detailed data registers that have common keys to combine data. There is also a stringent regulation on access to these data bases. For every land register in a city data exists on buildings, people and to some degree also on employees. An assessment of the usability of present data registers will be carried out e.g. the registers: Bolig- og bygningsregisteret (BBR) (Home and Building Register), Det Centrale Person Register (CPR) (Personal Register), Kommunernes Årsstatistik (KÅS) (Municipal Annual Statistics).

Scope of Project
The project will focus on human exposure and exclude medical assessments of dose and health effects. Focus will be on long-term exposure studying the seasonal, weekly and diurnal variation in air pollution levels and the similar temporal variation in people's time-activity pattern as they relate to different microenvironments. The main emphasis will be on modelling population dynamics as basis for exposure modelling i.e. theoretical and methodical considerations on the association between the temporal variation in air pollution and the variation in people's time-activity pattern. The aim is to establish an operationally mathematical description as basis for implementation in GIS.

The model will be implemented and tested in a case study. The town of Middelfart has been selected as data on road network, traffic and buildings is available in GIS (ArcView) from the GIS-T project. Since Middelfart only has about 12.500 inhabitants air pollution problems will be limited and the case study will be a pilot study for testing methodologies.

Analyses
The analyses will focus on exposure assessment but also give examples on how the exposure model may be used for health risk and impact assessment. The exposure assessment will include an analysis of the importance of different microenvironments and the difference in exposure between various population groups depending on differences in time-activity patterns. Different population exposure indicators will be compared: (a) a simple approach assuming a modelled fixed monitor station in the centre of the city as exposure indicator (b) assuming the dwellings where people live as exposure indicators (c) taking into account the population dynamics as outlined above. Furthermore, the results of the above population exposure indicators will be compared to personal exposure of hypothetical representative individuals modelled as case examples. Examples of health risk assessment will be given including comparison of modelled air pollution levels with air quality criteria and guidelines, and quantification of risk (e.g. benzene). Examples of impact assessment of selected traffic control strategies (e.g. all cars equipped with catalysts).

4. Anticipated Results and Perspectives

I anticipate to reach the following conclusions:
(a) the exposure levels differ significantly between and within different microenvironments
(b) traffic environments contribute significantly to total exposure (sh ort time spent in the environment but high concentrations)
(c) there is a distinct difference in personal exposure between different population groups due to differences in time-activity patterns
(d) fixed monitor stations overestimate population exposure
(e) data on time-activity patterns of different population groups is insufficient from an exposure point of view.

The perspective of the project is to lay the foundation for development of an Urban Air Quality Information and Management System for use by local authorities for urban and traffic planning purposes. Features could be:
(a) air quality assessment with mapping of the air quality and comparison with air quality guidelines
(b) on-line predictions of concentrations in combination with measurements from fixed monitor stations

(c) information to the public
(d) environmental impact assessment of traffic planning and urban development projects
(e) future projections and scenarios
(f) exposure assessment and health risk assessment

Examples of Urban Air Quality Management Systems established in other countries that encompass similar or selected features are the British Urban Air Quality Management System (ADMS) developed by Cambridge Environmental Research Consultants (CERC) or the Norwegian Environmental Surveillance and Information System (ENSIS) developed by the Norwegian Institute for Air Research (NILU).

To predict air pollution concentrations from point sources like stacks the Danish OML model may be implemented.

Other environmental impacts form traffic like energy consumption and emissions, traffic safety, noise, risk perception and barrier effect, and visual environment may be included together with traffic models.

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